L-FIRE: A Distributed Aperture CubeSat Radio Telescope

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***Abstract*—The Low-Frequency Interferometric Radio Explorer (L-FIRE) is a proposed space-based mission concept designed to unlock low-frequency radio observations in the 1–40 MHz range. Frequencies below approximately 10 MHz are inaccessible from the ground due to the Earth's ionosphere, while the 10–30 MHz regime is strongly affected by ionospheric distortion. L-FIRE addresses this gap using a distributed interferometric array of ten or more CubeSats operating in low Earth orbit, synthesizing a large effective aperture through evolving baselines. Taking advantage of the relaxed geometric requirements of long-wavelength radio interferometry, the mission avoids precision formation flying while benefiting from improved uv-plane coverage over time. The architecture incorporates dedicated processing nodes to accommodate realistic ground-segment constraints and enable onboard correlation and data reduction. Beyond its primary scientific objectives in heliophysics, planetary radio emission and cosmology, L-FIRE serves as a pathfinder for edge-enabled, distributed space platforms applicable to a broad range of future sensing missions.**

***Index Terms*—radio astronomy, CubeSat constellations, distributed interferometry, space-based radio telescopes, heliophysics, edge computing, distributed space platforms**

I. Introduction

Low-frequency radio astronomy aims to probe some of the most fundamental and dynamic physical processes in the Universe, spanning heliophysics, planetary science, transient LF radio emission and cosmology. Radio emission in the MHz regime traces non-thermal particle acceleration, plasma instabilities, and large-scale magnetic structures, offering unique diagnostic power that is complementary to observations at higher electromagnetic frequencies. However, frequencies below 10 MHz are inaccessible from the ground due to absorption, refraction, and distortion by the Earth's ionosphere, as well as contamination from terrestrial radio-frequency interference. This ionospheric cutoff represents a hard physical limit rather than a technological one, leaving the sub-10 MHz window as the last largely unobserved region of the radio spectrum [1].

Space-based observations are therefore required to fully unlock the scientific potential of low-frequency radio astronomy. Past and current efforts have demonstrated the feasibility of spaceborne radio receivers at long wavelengths, but have been largely limited to single-point measurements without true imaging capability [2]. Imaging at low frequencies is essential for localizing emission sources, disentangling spatially complex phenomena. Interferometry provides a natural path toward this imaging capability by synthesizing a large effective aperture from spatially separated antennas.

Recent advances in small-satellite platforms, timing systems and inter-satellite communication have made distributed interferometric observatories based on CubeSat constellations a realistic and attractive option. Rather than relying on rigid structures or precision formation flying, a swarm of small spacecraft can form a dynamic interferometric array in which orbital motion naturally evolves the baseline geometry over time, enhancing sampling of the spatial frequency (uv) plane. This improves image fidelity without requiring frequent station-keeping. As a result, low-frequency radio astronomy is well matched to distributed space systems, turning what would be viewed as a disadvantage in other domains into a scientific and operational advantage.

The Low-Frequency Interferometric Radio Explorer (L-FIRE) mission concept was developed and proposed as a candidate mission concept in the ESA F-class (F3) selection cycle. L-FIRE is a distributed aperture radio telescope composed of ten or more CubeSats, each equipped with a broadband dipole antenna, operating as a coordinated, time-synchronised array in Low Earth Orbit (LEO). By maintaining baselines between 5 and 50 kilometers, L-FIRE aims to achieve high sensitivity and reasonable angular resolution at frequencies from 1 to 40 MHz, including regimes entirely inaccessible from the ground. Beyond addressing key science questions in heliophysics, space weather, planetary radio emission and cosmology, L-FIRE is conceived as a pathfinder for future distributed space platforms, demonstrating scalable, geometry-tolerant and time-synchronised swarm architectures relevant not only to space observatories, but also to emerging applications in distributed sensing, Earth observation, radar and space environment monitoring. This paper presents the L-FIRE

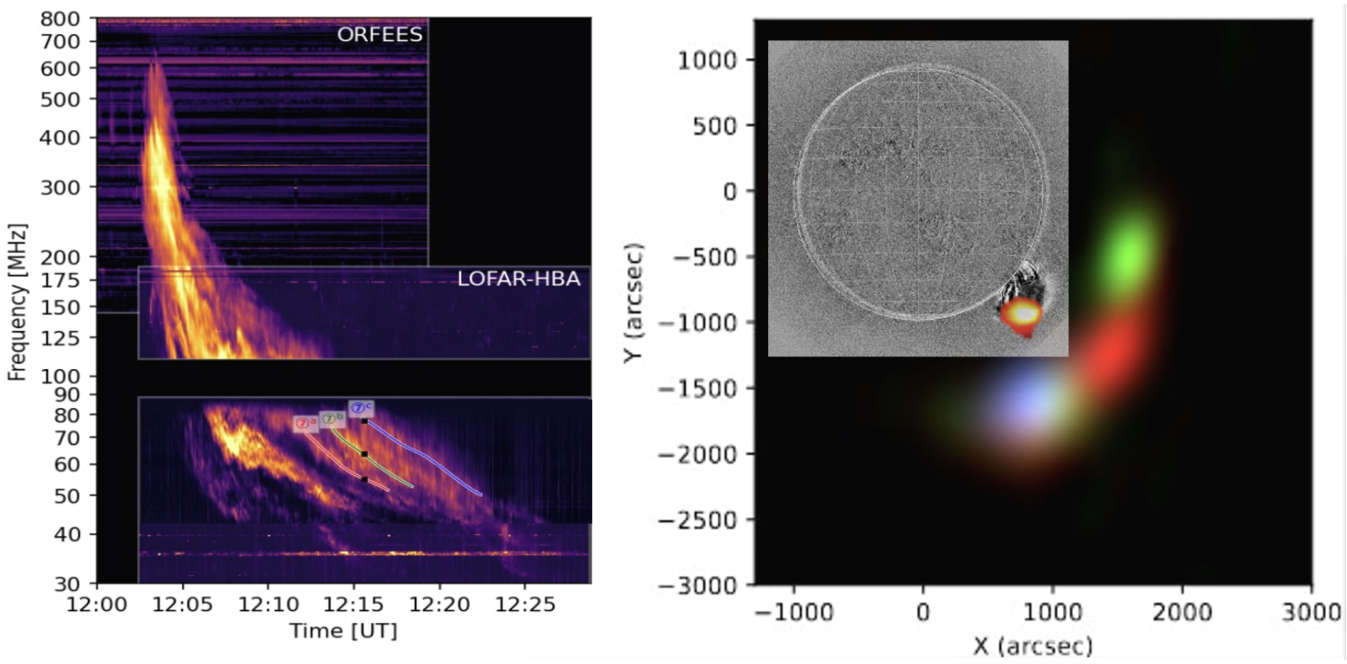


Fig. 1. Example of a shock signature (Type II radio burst) observed between 426 MHz and 40 MHz, corresponding to the lowest frequencies accessible from the ground (adapted from [3]). The left panel shows a composite dynamic spectrum of the Type II burst. The right panel presents radio imaging of the same event in the low solar corona. Colored sources indicate emission at 426 MHz (yellow) and three distinct shock locations along the CME front at 80 MHz (blue), 60 MHz (green) and 50 MHz (red). Ground-based observatories such as LOFAR can image the shock only out to heliocentric distances of approximately 2 R$\odot$. A space-based interferometer such as L-FIRE will extend spatially resolved imaging to much lower frequencies, enabling localization of burst emission across the heliosphere out to 1 AU (215 R$\odot$).

mission concept, its scientific motivation, and the core elements of its spacecraft and payload design.

II. Science Drivers and Observational Regimes

The L-FIRE operating frequency range was selected to span 1—40 MHz, encompassing the 1–10 MHz band that is completely inaccessible from the ground, the 10–30 MHz regime that is strongly affected by ionospheric distortion, and extending up to 40 MHz to allow direct comparison and cross-calibration with ground-based observatories such as the Low-Frequency Array (LOFAR).

The primary science driver for L-FIRE is heliophysics and space weather, where low-frequency radio observations play a central role. Solar radio bursts of Types II and III are generated by energetic electrons accelerated in association with solar flares and coronal mass ejections (CMEs). These bursts drift rapidly in frequency as the emitting electrons propagate through the decreasing plasma density of the corona and heliosphere, encoding information on particle acceleration and transport processes [3].

At frequencies below tens of MHz, radio emission originates progressively farther from the Sun, extending from the middle corona into interplanetary space. Imaging in this regime is essential for localizing the origin of the bursts, reconstructing shock geometries and tracking CME-driven disturbances out to large heliocentric distances. Ground-based instruments cannot access this region in a continuous and ionosphere-free manner, and existing space missions provide only spectral rather than imaging capabilities. A space-based interferometric array would enable the direct spatial tracking of shock features associated with CMEs and electron beams [4], [5], providing information for important physical properties and critical insight into the drivers of hazardous space weather events. An example of such a shock signature, observed at the lowest radio frequencies accessible from the ground, is shown in Fig. 1.

Low-frequency radio emission is also a powerful diagnostic of magnetospheric and plasma processes throughout the Solar System and beyond. Magnetised planets in our Solar System generate intense radio emission via cyclotron maser instability, with characteristic frequencies that, except for Jupiter, fall below the terrestrial ionospheric cutoff [6]. Continuous, space-based observations would enable comparative studies of planetary magnetospheres and their interaction with the solar wind, including Earth's own radio environment viewed from an external vantage point. Beyond the Solar System, low-frequency radio observations offer a means to investigate star–planet interactions, particularly for close-in exoplanets orbiting active stars, where magnetic coupling may produce detectable coherent emission.

At frequencies accessible to L-FIRE, the redshifted 21-cm line of neutral hydrogen offers a unique probe of the early Universe during the period prior to the formation of the first stars and galaxies called the Dark Ages [7]. The observed frequency of the 21-cm line scales as $\nu \approx 1420/(1+z)$ MHz, such that frequencies in the 1–40 MHz range correspond

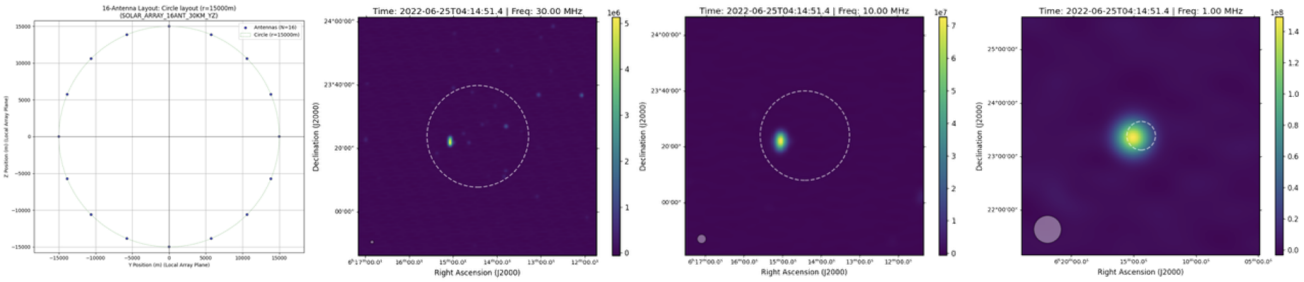


Fig. 2. Example of one possible satellite formation (left panel) and the corresponding image fidelity, indicated by the synthesized beam shown in the lower-left corner, at observing frequencies of 30, 10 and 1 MHz. The three right-hand panels show simulated images of a Type III radio burst generated using a real observational dataset from LOFAR. The dotted circle indicates the apparent size of the Sun. The simulations illustrate the frequency-dependent imaging performance of a distributed low-frequency interferometer, with decreasing angular resolution at longer wavelengths.

to redshifts $z \sim 35$–1400. In particular, the band between 10 and 40 MHz probes the later stages of the Dark Ages ($\sim$ 30–140), while frequencies below 10 MHz access even earlier epochs deeper into the Dark Ages. Measurements of the global 21-cm signal in this band could potently constrain the thermal and ionization history of the intergalactic medium, providing insight into fundamental processes such as baryon cooling, dark matter interactions and the initial growth of cosmic structure. Hovewer, measurements of the redshifted 21-cm signal at these frequencies are expected to be strongly affected by foreground emission, calibration uncertainties and radio-frequency interference (RFI). As such, cosmology with L-FIRE has mainly an exploratory objective that aims to assess feasibility and guide future mission concepts.

In addition, the MHz regime remains largely unexplored for transient and coherent radio phenomena. Together, these science cases motivate the need for a broadband, polarimetric and spatially resolving low-frequency radio instrument operating above the densest part of the ionosphere (F2 layer) where RFI is also manageable [8].

III. L-FIRE Mission Concept

As mentioned, the L-FIRE mission is designed as a space-based, distributed aperture radio telescope designed to operate in the low-frequency regime from 1 to 40 MHz in LEO orbit at around 700, which avoids most of the ionosphere. Its core architectural principle is the use of multiple small spacecraft operating cooperatively as an interferometric array, synthesizing a large effective aperture that cannot be realized with a single platform at these wavelengths. Taking advantage of the inherent advantages of long-wavelength interferometry and modern small-satellite technologies, L-FIRE adopts a mission design that is scientifically impactful and compatible with scalable and cost-efficient implementation.

1) Distributed Aperture Architecture: L-FIRE distributes its collecting area across a constellation of CubeSats, each carrying simple, broadband dipole antennas. The signals received at each node are timestamped and coherently combined to form an interferometric measurement of the radio sky. The spatial separation between spacecraft defines the interferometric baselines, with maximum separations of roughly 50 km enabling angular resolution that scales favorably with frequency across the mission band. The impact of spacecraft geometry and observing frequency on imaging performance is illustrated in Fig. 2, which shows a representative formation and the resulting simulated image fidelity at 30, 10 and 1 MHz.

At low radio frequencies, long wavelengths significantly relax mechanical and positional constraints compared to optical or high-frequency interferometers. Meter-level knowledge of relative spacecraft positions is sufficient to support accurate imaging, and absolute station maintenance is not required. This allows the constellation to operate as a dynamically evolving array in which natural orbital motion continuously changes the baseline geometry. Over time, this evolution increases the sampling of the spatial frequency (uv) plane, directly improving image fidelity and sensitivity without frequent propulsion or control effort [1], [9].

2) Observation Principle: Each L-FIRE spacecraft measures the incident electric field using orthogonal dipole antennas, providing sensitivity to polarization and total intensity. Signals from different nodes are synchronised in time and combined during post-processing to reconstruct spatially resolved radio images and dynamic spectra. This approach supports a wide range of observing modes, including high-cadence monitoring of rapidly evolving phenomena such as solar radio bursts, as well as longer integrations for faint or diffuse emission. The large instantaneous field of view inherent to dipole antennas allows L-FIRE to observe extended regions of the sky simultaneously, an important capability for tracking heliospheric events and monitoring transient phenomena. As constellation geometry evolves along its orbit, repeated snapshot observations can be coherently combined to improve sensitivity and angular resolution. Pointing requirements for low-frequency radio astronomy are modest compared to optical systems, as dipole antennas have intrinsically wide fields of view.

3) Mission-Level Design Philosophy: The L-FIRE mission adopts a design philosophy that prioritizes robustness, scalability and functional tolerance over geometric rigidity. Scientific measurement relies on relative timing and position knowledge rather than fixed spacecraft configurations, allowing the mission to accommodate drift, incremental deployment or partial

constellation availability. This makes the architecture inherently resilient to individual node failures and is well suited to phased implementation strategies. By avoiding the need for precision formation flying, L-FIRE reduces system complexity while exploiting the natural dynamics of orbital motion as an asset rather than a disadvantage. In this context, L-FIRE serves not only as a low-frequency radio observatory, but also as a representative example of how distributed CubeSat platforms can be used to realize large synthetic apertures for sensing applications in space.

IV. Spacecraft and Payload Overview

The L-FIRE mission is designed around a modular spacecraft concept in which each node of the interferometric array is implemented as an identical CubeSat. This approach supports scalability, simplifies integration and verification, and enables a flexible mission architecture in which the number of active elements can be adapted to mission constraints or expanded over time. The payload and spacecraft subsystems are co-designed to support low-frequency radio observations while remaining compatible with the constraints of small-satellite platforms. A summary of the key spacecraft, payload, and constellation parameters for the L-FIRE mission concept is provided in Table I.

The design of the L-FIRE mission concept is strongly influenced by the coupling between space-segment capabilities and the constraints imposed by the available ground segment. While advances in inter-satellite communication and space-to-ground links enable increasingly high data rates from individual spacecraft, scientific missions operated by non-commercial actors are often limited by shared or heritage ground infrastructure. In the case of L-FIRE, the assumed use of ESA-based ground segment places an upper bound on the sustainable downlink rate. For the L-FIRE concept, this constraint translates to an effective average science data return of approximately 8 Mbit/s, dictating key architectural choices at the mission level.

To accommodate this limitation while preserving interferometric performance, the L-FIRE constellation is organized around a separation of sensing and processing functions. The primary swarm consists of CubeSat sensing nodes that carry active antennas and front-end receivers, which acquire and digitize radio signals. The sensing nodes functions as an autonomous sensing element within the distributed array. The CubeSat platform provides essential services including power generation and storage, attitude knowledge and control, onboard data handling, timing and communication. From a mission perspective, the nodes are functionally equivalent, allowing the constellation to operate without reliance on any single spacecraft. This uniformity also enhances fault tolerance, as partial degradation of the constellation leads to graceful reduction in imaging performance rather than catastrophic mission failure.

The primary payload element on each CubeSat is a set of broadband dipole antennas optimized for the 1–40 MHz frequency range. Dipoles are lightweight and mechanically simple. Orthogonal antenna orientations enable polarimetric measurements, which are important for diagnosing emission mechanisms and propagation effects in plasma environments. The signals received by the antennas are processed by low - noise radio-frequency front-ends that condition and digitize the incoming waveforms. At these frequencies, sensitivity is often limited by the natural sky background (”sky noise”) rather than receiver noise, allowing spectrally wide observations with relatively simple analog architectures.

The sensing nodes are followed on the orbital track by two dedicated spacecraft that serve as processing nodes. Rather than transmitting raw voltage data directly to the ground from all nodes, the processing nodes receive data from the swarm, perform correlation and data aggregation, and manage storage and downlink operations. This architecture reduces the burden on the ground segment while enabling efficient use of the available telemetry capacity. Operating in LEO at an altitude of approximately 700 km, each processing node has on the order of 15 minutes of visibility per ground station pass. Preliminary calculations indicate that L-FIRE would generate 20–25 minutes worth of accumulated correlated data per orbit. The use of two processing nodes enables a ”handover” strategy: the first node initiates transmission during its ground-station visibility window, and upon loss of contact, the second node continues and completes the data transmission during its subsequent pass. Redundancy between the processing nodes also enhances data integrity and mission robustness by reducing the risk of data loss.

Preliminary orbital analyses indicate that the relative geometry of the constellation remains within acceptable bounds over extended periods without active station keeping. For nominal initial conditions, the inter-satellite separation remains within a minimum distance of approximately 5 km and a maximum distance of approximately 50 km for at least 40 consecutive orbits. This stability implies that only limited orbital correction maneuvers would be required over the nominal two-year mission lifetime.

Interferometric operation requires accurate time synchronization across the constellation to preserve phase coherence between signals received at different nodes. Therefore L-FIRE relies on synchronized clocks and precise time tagging of the sampled data to provide on-board correlation and further ground-based post-processing. Importantly, the required timing accuracy scales with observing wavelength, allowing microsecond-level synchronization to be sufficient for low-frequency operation.

In summary, relaxed formation control requirements, combined with the processing-node data architecture, reflect a system-level optimization in which scientific objectives, space-segment capabilities and realistic ground-segment constraints are treated coherently within the overall design of the mission.

V. Summary and Outlook

The L-FIRE mission concept highlights how low-frequency radio astronomy occupies a unique position among

TABLE I
SUMMARY OF L-FIRE CUBESAT NODE CHARACTERISTICS

Parameter	Nominal Characteristics
Platform class	CubeSat-class spacecraft
Spacecraft role	Interferometric array node
Number of nodes	$\geq$10 (scalable constellation)
Frequency range	1–40 MHz
Antenna type	Orthogonal deployable dipole antennas
Polarization capability	Dual-linear (full Stokes capability)
Field of view	$\sim$All-sky (dipole-limited)
Baseline lengths	5–50 km
Position knowledge	Meter-level relative accuracy
Timing synchronization	Microsecond-level (wavelength-scaled)
Onboard processing	Signal conditioning, digitization, buffering
Data correlation	On-board processing
Attitude requirements	Low, driven by operations and antenna geometry
Constellation control	Passive drift, no precision formation flying
Mission lifetime	Technology- and orbit-limited (order of 2 years)
Primary science targets	Solar, heliospheric, planetary, transient LF radio emission and cosmology
Pathfinder relevance	Distributed space platforms and sensing architectures

space-based sensing systems, where access to space is driven by fundamental physical limitations rather than incremental performance gains. By targeting the 1–40 MHz frequency range, L-FIRE addresses a long-standing observational gap at low radio frequencies while providing overlap with ground-based instruments for calibration and validation. In this sense, L-FIRE represents an important step toward unlocking the last unexplored window of the radio spectrum.

From an architectural perspective, L-FIRE demonstrates that long-wavelength radio interferometry is exceptionally well suited to distributed satellite systems. The relaxed requirements on baseline knowledge and timing precision, combined with the benefit of naturally evolving geometries, remove the need for precision formation flying and continuous station keeping. Instead, orbital motion and relative drift enhance interferometric performance by improving uv-plane coverage over time. Furthermore, the separation of sensing nodes and processing nodes reflects a pragmatic response to realistic ground-segment constraints and illustrates how system-level optimization must account for both space- and ground-based resources.

Beyond its immediate scientific objectives, L-FIRE is deliberately conceived as a modular building block for future distributed space platforms. The core principles demonstrated by the mission – scalable swarms, tolerant geometries, synchronized sensing and centralized or semi-centralized processing – are applicable across a wide range of disciplines, including Earth observation, distributed radar, space weather monitoring, and future sparse-aperture observatories. The mission concept therefore offers multiple entry points for collaboration with industry, research institutions and agencies, spanning spacecraft platforms, low-frequency RF technology, inter-satellite communication, autonomy, and edge computing and data processing. In this broader context, L-FIRE serves both as a scientifically motivated mission concept and as a system-level pathfinder for the next generation of distributed space systems.

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